SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

1. Report No. | 2. | 3. Accession No. W 72-12121

4. Title: Evaluation of Processes Available for Removal of Phosphorus from Wastewater

5. Report Date

6.

7. Author(s): Cecil, Lawrence K.

8. Performing Organization Report No.

10. Project No. 17010 DRF

9. Organization: ~~Lawrence K. Cecil, P.E. Consulting Chemical Engineer Tucson, Arizona 85704~~

11. Contract/Grant No. Contract 14-12-581

13. Type of Report and Period Covered

12. Sponsoring Organization

15. Supplementary Notes

Environmental Protection Agency Report No. EPA-R2-72-034, Oct. 1971, 4 p, 39 ref

16. Abstract

The more important treatment processes for removal of phosphorus compounds from municipal wastewater are evaluated for practicality, cost, and impact on the quality of the treated effluent. The ~~bewildering number of~~ options for the designer in the selection of treating processes, chemicals to be used, and the point or points of chemical application are discussed. A detailed list of phosphorus removal projects ~~in the office~~ of one consulting engineer is given as an example of phosphorus removal projects under design. A list of full-scale phosphorus removal plants, already in operation or planned, shows the type of treatment selected and the operating results expected. Various methods of ultimate sludge disposal are discussed.

17a. Descriptors: Sewage Treatment, Phosphates, Biological Treatment, Chemical Precipitation, Activated Sludge, Physical Processes, Tertiary Treatment, ~~Process Selection~~.

17b. Identifiers: Sludge Production, Lime, Alum, Iron, Aluminate, ~~Cost~~.

17c. COWRR Field & Group: 05D

Available from the National Technical Information Service as PB ~~93.09~~ in paper copy, $0.95 in microfiche $3.75

18. Availability: PB-211191

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages

22. Price

Send To: WATER RESOURCES SCIENTIFIC INFORMATION CENTER U.S. DEPARTMENT OF THE INTERIOR WASHINGTON, D. C. 20240

Abstractor: L. K. Cecil

Institution

WRSIC 102 (REV. JUNE 1971) GPO 913.261

W72-12121

EPA-R2-72-034
July 1972

PB 211 191

EVALUATION OF PROCESSES AVAILABLE FOR REMOVAL OF PHOSPHORUS FROM WASTEWATER

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ENVIRONMENTAL PROTECTION AGENCY

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Springfield VA 22151

Project #17010 DRF
Contract #14-12-581

October 1971

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A detailed list of phosphorus removal projects in the office of one consulting engineer is given as an example of phosphorus removal projects under design.

A list of full-scale phosphorus removal plants, already in operation or planned, shows the type of treatment selected and the operating results expected.

Various methods of ultimate sludge disposal are discussed.

This report was submitted in fulfillment of Project Number 17010 DRF, Contract Number 14-12-581 under the sponsorship of the Environmental Protection Agency.

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SECTION I

CONCLUSIONS

1. A critical survey of presently available treatment processes for the removal of phosphorus compounds from municipal wastewater shows that present technology is capable of meeting the standards for disposal of the treated effluent.

2. Processes are available to add to existing plants at minor capital investment to give good phosphorus removal, with simultaneous improvement of plant operation in general.

3. Sludge disposal must take into account the mass caused by chemical residues, and new air and land pollution control regulations.

4. Changing quality disposal standards, and the possibility of requirement for nitrogen removal also, requires careful process selection.

5. Analysis of data from a number of bench-scale, pilot plant and full-scale plant operation indicate that the overall objectives of municipal wastewater treatment, including phosphorus removal, will be realized best by a combination of biological and physical-chemical treatment rather than straight biological or physical-chemical treatment.

SECTION II

RECOMMENDATIONS

Until the mechanism of luxury phosphorus uptake is understood, it is not possible to evaluate its general application. It has so many desirable features that research to unravel this mystery should be encouraged.

Acid iron and aluminum salts add sulfates or chlorides to the effluent. Alkaline aluminum salts add sodium. The electrochemical method using sacrificial aluminum or iron electrodes adds only the cation hydrogen which is dissipated harmlessly to the air. Its cost is comparable to the use of metal salts. It should be thoroughly evaluated for general use.

There should be developed for aluminum and iron precipitation reactions a control method similar to pH control for lime treatment. Streaming current measurement of zeta potential, set to vary chemical feed to maintain zero zeta potential, is one possibility that should be studied.

Transportation and storage of treating chemicals and ultimate disposal of the chemical-loaded sludge create serious problems. Methods of reuse of the metal values should be developed. Processes for recovery and reuse of lime are already in use. Processes for recovery for reuse of aluminum and iron should be developed.

SECTION III

INTRODUCTION

With the public demand for prevention of eutrophication of our lakes and streams, control of plant nutrients in wastewater has become of importance. Of the major nutrients other than carbon, removal of phosphorus is most easily controlled.

There is an enormous and sometimes confusing literature on the many processes for phosphorus removal. Many exotic processes have been studied, and some show promise. The well-known chemical precipitation processes have been studied intensively to establish design criteria that can be used with assurance by the consultant. The occasional startling complete removal of phosphorus by luxury uptake incidental to regular activated sludge operation has been studied without success to establish the criteria for universal operation.

The scientific and technical details of the various processes are thoroughly outlined in many articles, some of which are listed as reference. No effort is made here to repeat these details. Instead, a listing of the good and bad features of the several practical processes is given to help the design engineer decide which process to use and how to apply it to each installation.

It is of interest that, except for controversy about the mechanism of luxury uptake, there is reasonable agreement about the mechanism and application of other processes.

Phosphorus is present in municipal wastewater in many forms. In untreated wastewater there will be organically-bound phosphorus, and the inorganic phosphorus will be a mixture of orthophosphate and condensed phosphates, principally pyrophosphate and triphosphate. These condensed phosphates hydrate to orthophosphate under a variety of conditions. Very high or very low pH and enzymatic action are the dominant mechanisms. In biologically treated wastewater nearly all of the complex forms have been degraded to the orthophosphate by enzyme action.

For each installation the various methods are evaluated in terms of cost, both capital investment and operating, adaptability to existing equipment, available chemicals, and complexities of sludge disposal. An additional important parameter is the use of the treated effluent. If it is to be reused then added ions such as sodium, sulfates, and chlorides would be objectionable. Most phosphorus removal systems have additional beneficial results, such as increased reduction of suspended solids and BOD. These results should have a place in the evaluation.

Selection of the technique for each individual case will be governed by overall cost. Capital investment including land value, operating costs such as chemicals, power, labor, and sludge disposal are the obvious costs. Reliability must be evaluated, because there is a cost, tangible or intangible, for operating failures.

Phosphorus removal requires a series of unit operations. First, the phosphorus must be insolubilized. Second, the solid must be separated from the liquid. Third, the solid must be disposed of so it will not contaminate the environment. Each operation must be performed properly to produce the very low phosphorus concentrations required now, or in the future, in the final effluent.

Municipal wastewater varies continually in volume and in chemical demand. Control equipment must be able to measure continuously both variables and send an integrated signal to the chemical feeding equipment to vary chemical feed to keep pace with chemical demand. The treating chemical may react with constituents other than phosphates, thus complicating the control problem. Precipitation of orthophosphates by iron or aluminum compounds takes precedence over neutralization of electrical charges on colloids. A continuous phosphate analyzer can signal the concentration of orthophosphate. This must be integrated with a continuous flow measurement. The integrated signal can be sent to an automatic chemical feeder that has been manually adjusted for the proper Al:P or Fe:P ratio for the particular chemical being applied. This takes care of phosphate precipitation, but does not satisfy the additional chemical demand for neutralization of the electrical charges on the colloids. Good coagulation and gravity liquid-solids separation will not be obtained until both chemical demands are satisfied. A streaming current detector set for zero zeta potential with electrical controls on the chemical feeder to supply more or less chemicals as the measurement goes below or above the set point would give control of both chemical demands. The width of the hunting band above and below the set point will govern the success of the operation. Broad control devices for precipitation reactions, such as pH for lime, zeta potential for aluminum and iron salts, or a large excess of a solid insoluble reactant as in percolation columns of aluminum oxide are good control methods.

A comprehensive view of the processes is given in two review articles, one biological (1) and the other chemical (2).

SECTION IV

TREATMENT SYSTEMS

Treatment techniques fall into three broad classifications; physical, biological, and chemical. Historically, municipal wastewater plants have been designed and operated to minimize oxygen depletion in the receiving body of water, and to eliminate disease producing organisms. These objectives are not adequate to meet modern disposal requirements, which in some cases require substantial reduction in the phosphorus content of the effluent. Efficient methods of reducing phosphates in wastewater, such as precipitation with lime or iron and aluminum salts, have been practiced for many years in industrial water softening installations.

Application of these techniques to municipal wastewaters is not simple. Almost never is softening with associated phosphorus reduction the objective. Instead, reduction of biological oxygen demand by removal of biologically oxidizable carbon compounds is a universal need. Sometimes the slower biological oxygen demand of nitrogen compounds must also be reduced. Thus, the selection and design of the phosphorus reduction system is influenced by other treatment requirements. It is of interest that the two principal nutrients for eutrophication are carbon and nitrogen so their removal for prevention of oxygen depletion in the receiving water aids in eutrophication control. When we add phosphorus reduction we have a symbiotic relationship that benefits all the requirements. Almost all phosphorus reduction methods, particularly if applied to the head of the plant, also remove some carbonaceous and sometimes nitrogenous compounds.

Phosphorus reduction systems are incorporated into entirely new plants, existing plants that are to be increased in capacity, and in existing plants without capacity increase. They may be physical-chemical, physical-biological, or physical-biological-chemical. All will need a system of sludge stabilization, which may be biological digestion or incineration.

Most of the chemical precipitation methods for the removal of phosphorus compounds from wastewater depend on the use of soluble salts of the metal. Calcium oxide (lime) is the only oxide soluble enough to be used directly as a treating chemical. Iron, both ferrous and ferric, and aluminum are used as the sulfate and chloride salts. Aluminum is sometimes used as sodium aluminate. The classical solubility product relationships based on relatively pure water are not applicable to precipitation processes in the complex environment of municipal wastewaters. In some cases the evidence is not clear as to whether the reaction is precipitation, adsorption, or both (9)(10).

A promising method of using sacrificial electrodes of either iron or aluminum has been pilot planted by Sadek (12). It gives practically complete removal of phosphate without introducing pH problems. The cost for electrode metal and current is nominal, about 2.5 cents/1000 gal. and 8.0 cents/1000 gal. when using iron and aluminum electrodes, respectively. It is currently being operated on raw sewage in a 75,000 gpd (284 m^3) pilot unit by the City of Odessa, Texas and Pollution Engineering International, Inc. of Houston, Texas.

The use of high surface area aluminum oxide in packed columns has been shown to be practical (11). The aluminum oxide is reactivated by flushing with a sodium hydroxide solution. In order to avoid a large liquid waste, the regenerant is treated with lime to precipitate the phosphates, and fortified with new caustic for reuse. The large capital investment will limit the use of this system. It does have the advantage of an excess of the reactant, which compensates for variable phosphorus content of feed.

There are some deficiencies in even a well-operated secondary type biological plant such as the inability to remove non-biodegradable organics. For this and other reasons there is a growing tendency to use physical-chemical treatment processes. The best developed of the physical-chemical processes are those involving a primary chemical precipitation clarification unit for removal of suspended matter and phosphates, followed by activated carbon columns for removal of residual, soluble organics. Here the chemical is added to the primary clarification system. Inasmuch as there is no further removal of phosphate after the chemical precipitation unit, the dosage must be used to get the desired amount of phosphate removal. This is in contrast to the biological secondary treatment systems in which cell synthesis will remove additional amounts of phosphate.

Selection of the treating system will be influenced by the method of sludge handling. Most existing treatment plants have anaerobic digesters. The calcium-phosphorus precipitate is solubilized in the anaerobic environment, thus returning the phosphate to the supernatant. The aluminum-phosphorus and the iron-phosphorus precipitates are not solubilized (8). Thus, aluminum or iron salts can be used with no change in the conventional operation of anaerobic sludge digestion with the supernatant returned to the system.

Incorporation of phosphorus into the aerobic floc in metabolic uptake and chemical precipitation of phosphorous compounds is only one unit process - insolubilizing of the phosphorus. Effective liquid-solid separation is necessary to remove the now insoluble phosphorus from the system.

Gravity separation in clarifiers equipped with sludge scrapers for thickening of the sediment is universally practiced in both primary and secondary clarifiers. Some of the precipitates do not coagulate and settle well, with a substantial carry-over of precipitate in the liquid overflow. The use of a small amount of organic polymer as a coagulant aid is very effective both in reducing the carry-over of suspended solids and in producing a denser underflow.

Granular bed filters for removal of the small amount of suspended solids carry-over from the clarifier should be the final unit operation in liquid-solids separation. Insolubilization of the phosphorus to less than 0.1 mg/l P in the liquid fraction loses its benefit if 10 or 20 mg/l of phosphorus precipitate enters the aqueous environment to be again solubilized in the anaerobic environment at the bottom of streams and lakes over a long time period.

Stabilization of the separated insoluble phosphorus is the final unit process. Biological digestion (both anaerobic and aerobic) of the organic fraction of the sludge leaves a small amount of humus-like material that is biologically inert. The lime-phosphorus precipitate will be solubilized by anaerobic digestion but not by aerobic digestion. The aluminum and iron phosphorus precipitates will not be solubilized by either digestive process. Incineration of the sludge destroys all of the organic fraction and reduces the volume of the inorganic fraction by complete removal of water of hydration. The residues from these stabilization processes must go to an ultimate disposal system that will not permit them to re-enter the environment adversely.

BIOLOGICAL

In most municipal wastewaters carbon is the limiting bacterial nutrient in reduction of the biological oxygen demand. Phosphorus and nitrogen are present in much greater quantities than required for cell synthesis.

In some special cases bacteria have the ability to store up phosphorus in excess of synthesis requirements. Their dry weight may contain as much as 7% phosphorus (3). San Antonio, Texas (4), Baltimore, Maryland (5), and the Hyperion Plant at Los Angeles, California (6) are some of the better known examples. In these cases the enhanced capacity for phosphorus assimilation produces almost complete removal of phosphorus by the time the biologically oxidizable carbon has been utilized. In other cases, such as Manassas, Virginia (7), even though the bacteria have this enhanced capacity for phosphorus assimilation, the oxidizable carbon is not enough to produce sufficient cell synthesis for complete removal of phosphorus.

After the initial study by the Federal Water Quality Administration of successful luxury phosphate removal at San Antonio, a series of amenability studies were made at activated sludge plants in the United States. Although the results indicated some success in predicting luxury uptake, subsequent developments make these predictions less certain. The work of Yall and associates (13)(14)(15) and unpublished work by Garber at the Hyperion plant at Los Angeles definitely established that the process is metabolic rather than chemical precipitation.

The evidence is succinctly summed in the following statement:

> "Activated sludges obtained from the Rilling Road plant located at San Antonio, Texas, and from the Hyperion treatment plant located at Los Angeles, California, have the ability to remove all of the orthophosphate normally present in Tucson sewage within 3 hours after being added to the wastewater. Phosphorus removal was independent of externally supplied sources of energy and ions, since orthophosphate and ^{32}P radioactivity were readily removed from tap water, glass-distilled water, and deionized water. Phosphorus uptake by Rilling sludge in the laboratory appears to be wholly biological, as it has an optimum pH range (7.7 to 9.7) and an optimum temperature range (24 to 37° C). It was inhibited by $HgCl_2$, iodoacetic acid, p-chloromercuribenzoic acid, NaN_3, and 2,4-dinitrophenol (compounds that affect bacterial membrane permeability, sulfhydryl enzymes, and adenosine triphosphate synthesis).

> Uptake was inhibited by 1% NaCl but was not affected by 10-3M ethylenediaminetetraacetic acid disodium salt (a chelating agent for many metallic ions)."

Olson and Connell (16) submit experimental evidence for biological phosphorus and magnesium co-enrichment of activated sludge in luxury uptake of phosphorus from wastewater.

> "A mole ratio of approximately 1/3, Mg/P, was observed; in magnesium and phosphorus content of activated sludge, when P content in the solids was 1.5% to 4.5%, dry weight basis; in uptake of Mg and P, when through-plant removal of P was higher than 40%; at time of high uptake of P by aeration solids; at time of anoxic release of P enrichment of solids; and when there was release from solids by re-supply of nutrients sufficient to re-establish exponential growth of cells."

Culp, in the discussion following presentation of a paper on nutrient removal at the South Lake Tahoe plant where phosphorus is removed by tertiary lime treatment, said that once the activated sludge plant suddenly began to reduce phosphorus to 0.1 mg/l. An effort was made to keep the operating parameters unchanged, but after about ten days the luxury uptake stopped.

Extensive studies of luxury uptake at the Baltimore, Maryland activated sludge plant, where the process can be turned on or off at will by varying some of the known parameters, calcium removals show that the principal process is not chemical precipitation.

At San Antonio, Texas where one of the three parallel basins consistently reduces the phosphorus to less than 0.1 mg/l, the aeration and flow patterns of the other basins were modified to conform to the first, producing the same low residual phosphorus concentration.

The Hyperion activated sludge plant at Los Angeles, California consistently reduces the 12 mg/l P to less than 0.5 mg/l P at the outlet of the final clarifier without more than 2.0 mg/l dissolved oxygen at any point in the aeration basin. The much smaller Valley plant (originally designed for chemical precipitation but converted to activated sludge) will be modified to conform to the known operating parameters at the Hyperion plant in an effort to improve the present reduction of 12 mg/l P to 4 mg/l P to the low value of 0.5 mg/l of the Hyperion effluent.

Sludge volume at luxury uptake plants is essentially the same as at similar plants without luxury uptake. There must be enough excess sludge production so the weight of the sludge times the phosphorus content will equal the phosphorus content of the influent sewage.

The mechanism of enhanced phosphorus uptake is not known, and therefore is not controllable. On the basis of present knowledge, an activated sludge plant cannot be designed for enhanced phosphorus uptake. If an individual plant has this capacity for enhanced phosphorus uptake incidental to biological carbon oxidation, it should be considered a fortunate circumstance and the operating conditions known to be required should be maintained. Metabolic luxury uptake of phosphorus in activated sludge plants is an important mechanism for low cost removal of phosphorus from wastewater. If continuing studies establish the removal mechanism, universal application in activated sludge plants may become possible.

LIME

Lime precipitation of orthophosphate is a controllable reaction that follows stoichiometric calculations. At the high pH's 11.0-11.5 needed for almost complete removal of P, some of the condensed phosphates may be hydrolyzed to the ortho form, and some organic phosphorus compounds are coagulated. Lime can be added to the primary clarifier for P reduction but because not all of the condensed phosphates are hydrolyzed to the ortho form, and some of the orgamic phosphorus compounds are not precipitated, very low residual P cannot be obtained. With biological treatment preceeding the lime treatment, most, perhaps all of the condensed and organic phosphorus compounds will be converted to the ortho form. Thus, with good liquid-solid separation very low residual P can be obtained. The effluent pH from primary lime treatment may be too high for subsequent biological treatment, requiring pH reduction. With a lime-activated carbon system instead of a lime-biological system a final clarifier is not needed, but a filter is. Before disposal the pH must be reduced as required by stream standards. This is done by recarbonation or mineral acids.

An advantage of lime treatment is that no anion such as sulfate or chloride is added to the water.

If lime is applied to secondary effluent, a complete additional reaction and clarification unit is required, at a large additional capital investment.

Calculation of the lime required for removal of phosphorus from wastewater must take into account the fact that lime reacts also with several of the other constituents of municipal wastewater. These are free carbon dioxide, half bound carbon dioxide, magnesium, and the ammonium ion.

Calculation of the lime required for inorganic phosphorus removal is based on three assumptions.

1. Condensed phosphates will be hydrolyzed to the ortho form.

2. The phosphorus precipitate will be calcium hydroxyapatite, $Ca_5(OH)(PO_4)_3$.

3. Lime is added in excess of precipitation requirements to produce the desired pH of 11.0 or higher.

Typical equations are:

$3NaH_2PO_4 + 5Ca(OH)_2 = \underline{Ca_5(OH)(PO_4)_3} + 3NaOH + 6H_2O$

$H_2O + XCa(OH)_2 =$ desired pH

$CO_2 + Ca(OH)_2 = \underline{CaCO_3} + H_2O$

$Ca(HCO_3)_2 + Ca(OH)_2 = \underline{2CaCO_3} + 2H_2O$

$Mg(HCO_3)_2 + 2Ca(OH)_2 = \underline{Mg(OH)_2} + \underline{2CaCO_3} + 2H_2O$

$MgSO_4 + Ca(OH)_2 = \underline{Mg(OH)_2} + CaSO_4$

$2NaHCO_3 + Ca(OH)_2 = \underline{CaCO_3} + Na_2CO_3 + 2H_2O$

$Na_2CO_3 + Ca(OH)_2 = \underline{CaCO_3} + 2NaOH$

$NH_4HCO_3 + Ca(OH)_2 = \underline{CaCO_3} + NH_3 + 2H_2O$

If the listed constituents are known, then a reasonably accurate calculation of calcium hydroxide requirements can be made.

These equations are based on the assumption that practically complete removal of P is needed. At a sufficiently high pH, on the order of 11.0-11.5, the P content can be reduced to less than 0.1 mg/l in a filtered effluent.

Wastewater with a high content of sodium bicarbonate is not a good candidate for lime treatment. The high pH of 11.0 or more is produced by sodium hydroxide instead of calcium hydroxide when the wastewater does not contain sodium bicarbonate.

A typical example is Lancaster, California where the waste water has an average total alkalinity of 250 mg/l and an average hardness of 75 mg/l. Some of this alkalinity in excess of the hardness is caused by ammonia, but most of it is from sodium bicarbonate. Extensive pilot plant studies of treatment to make the wastewater suitable for make-up to a recreational lake showed that aluminum sulfate treatment was superior to lime treatment.

Many communities using well supplies have water with some sodium bicarbonate. These range from some with high alkalinities consisting almost entirely of sodium bicarbonate to those with a high calcium and magnesium bicarbonate but

with enough sodium bicarbonate to produce the pH of 11.0 caused by sodium hydroxide.

It is not practical to calculate the lime requirements for lower pH ranges. Instead, jar tests should be run to give a reasonable estimate of the plant scale requirements.

Sludges produced by lime treatment dewater readily. As pointed out earlier, they should not be subjected to anaerobic digestion if the supernatant is to be returned to the head of the plant. Incineration of the dewatered sludge will destroy the organic content, will convert the calcium carbonate to calcium oxide, the magnesium hydroxide to magnesium oxide, and may convert the hydroxyapatite to calcium oxide and tricalcium phosphate. If the ash from the incineration is slaked, only the calcium oxide slakes readily, leaving the calcium phosphate and magnesium oxide. Incineration of the sludge is a complex process. South Tahoe Public Utility District, South Lake Tahoe, California (18) reports in detail its study and practice on recovery of lime for reuse at its advanced waste water treatment plant.

ALUMINUM

Aluminum is used for phosphorus removal as both acid and alkaline soluble salts, as a sacrificial electrode, and as the oxide in granular contact beds. The latter two methods have not been used in full scale plants. The direct chemical reactions of the soluble salts are:

$$Al_2(SO_4)_3 + 2NaH_2PO_4 = \underline{2AlPO_4} + Na_2SO_4 + 2H_2SO_4$$

$$AlCl_3 + NaH_2PO_4 = \underline{AlPO_4} + NaCl + 2HCl$$

$$Na_2Al_2O_4 + 2NaH_2PO_4 = \underline{2AlPO_4} + 4NaOH$$

$$H_2SO_4 + Ca(HCO_3)_2 = CaSO_4 + 2CO_2 + 2H_2O$$

$$2HCl + Ca(HCO_3)_2 = CaCl_2 + 2CO_2 + 2H_2O$$

$$NaOH + CO_2 = NaHCO_3$$

The mole ratio of aluminum to phosphorus is 1:1

The weight ratio of aluminum to phosphorus is 0.97:1

The weight ratio of $Al_2(SO_4)_3 \cdot 14H_2O$ to phosphorus is 9.6:1

The weight ratio of $Na_2Al_2O_4$ to phosphorus is 3.6:1

Removal of condensed phosphates by precipitation with aluminum salts is dependent on pH and reactant concentration. At an Al:P ratio of 2:1 maximum removal of pyrophosphate and triphosphate occurs at pH 5.5. At pH values one unit above or below this value practically no condensed phosphate removal occurs. At an Al:P ratio of 1:1 even in the optimum pH range there is very little condensed phosphorus removal. At an Al:P ratio of 2:1 and optimum pH pyrophosphate is reduced to 0.9 mg/l P and triphosphate to 3.8 mg/l P.

IRON

Iron for phosphate removal may be in several forms, usually as the ferrous and ferric sulfate or chloride, and the metal in the form of a sacrificial electrode. Waste pickle liquor from metal manufacturing and working operations will have the metal present as ferrous sulfate or chloride, with an excess of the mineral acid. Some wastewaters may not have enough alkalinity to neutralize the excess acid and the anion of the ferrous salt, requiring addition of an alkali to maintain proper pH.

There appears to be little difference in efficiency of phosphorus removal between the ferrous and ferric forms. In an aerobic system the ferrous iron will be oxidized to the ferric form, adding a small additional load to the aeration system.

The simplest treating system is discharge of the waste pickle liquor directly into the sewer if it can be done without damage to the pipe. At Milwaukee, Wisconsin the insoluble iron and phosphorus content of the screened raw sewage is very high, leaving a small amount of soluble phosphorus in excess of cell synthesis requirements to be removed by inplant treatment with pickle liquor. At Cleveland, Ohio the Easterly plant removes 30% of the phosphorus, while at the Southerly plant the removal rate is 70%. The difference is discharge of metal working waste liquors into the sewers serving the Southerly plant.

The chemical and physical problems involved in iron salt precipitation, and the effect of such parameters as temperature, pH, time and the nature of the precipitates produced are analyzed by Recht and Ghassemi (9)(19).

The principal chemical reactions of both ferrous (+2) and ferric (+3) iron with orthophosphate are:

$$3Fe^{+2} + 2PO^{-3} = \underline{Fe_3(PO_4)_2}$$

$$3FeSO_4 + 2NaH_2PO_4 = \underline{Fe_3(PO_4)_2} + Na_2SO_4 + 2H_2SO4_4$$

$$3FeCl_2 + 2NaH_2PO_4 = \underline{Fe_3(PO_4)_2} + 2NaCl + 4HCl$$

$$Fe_2(SO_4)_3 + 2NaH_2PO_4 = \underline{2FePO_4} + Na_2SO_4 + 2H_2SO_4$$

$$FeCl_3 + NaH_2PO_4 = \underline{FePO_4} + NaCl + 2HCl$$

The mole ratio of ferrous iron to phosphorus is 3:2

The weight ratio of ferrous iron to phosphorus is 3.2:1

The mole ratio of ferric iron to phosphorus is 1:1

The weight ratio of ferric iron to phosphorus is 1.8:1.

Soluble ferrous iron oxidizes rapidly to ferric iron in the presence of dissolved oxygen. This reaction is minimal in a primary clarifier, but will go to completion in an activated sludge aeration basin. Temperature ranges found in municipal wastewater systems have little effect on the efficiency of phosphorus removal with metallic hydroxides. Orthophosphate removal with iron compounds is pH dependent. Optimum pH for ferrous iron is in the range of 7.0 to 8.0. Fortunately, this is the pH range of most raw sewages. For ferric iron it is much lower, in the range of 3.5 to 4.0, but efficiency is still high enough at the pH range of operating sewage plants to make its use practical.

The removal efficiencies for pyrophosphate and triphosphate with both ferrous and ferric compounds roughly parallels that of aluminum salts. Also the iron must serve the dual purpose of precipitating phosphates and neutralizing charges on negatively charged colloidal particles.

The settling characteristic of the precipitates at the pH resulting from the chemical reactions sometimes is poor, requiring the addition of an organic polymer for effective clarification.

SECTION V

POINTS OF CHEMICAL APPLICATION

One of the critical factors in phosphorus removal plant design is the point, or points, of chemical application. The range of design opportunities covers:

1. New Plants.

    A. Biological oxidation

        (a) Activated sludge
        (b) Trickling filter

    B. Chemical Precipitation

        (a) Primary only
        (b) Primary followed by biological oxidation
        (c) Primary followed by activated carbon
        (d) Biological secondary
        (e) Biological tertiary

    C. Physical

        (a) Ultrafiltration
        (b) Reverse osmosis

2. Existing Plants.

        (a) Any combination of 1A, B and C

3. Expanding Existing Plants.

        (a) Enlarging existing design
        (b) Expanded capacity as a new parallel plant

The phosphorus removal requirements established by the control authorities varies with location. Usually it is given in percent removal. Sometimes it is given in total pounds per day regardless of the total volume of treated sewage. It may be in residual phosphorus concentration.

Selection of the treating process is influenced not only by the phosphorus removal requirement, but also by suspended solids, BOD, and in a few cases residual nitrogen compounds. For example, chemical precipitation coagulation-clarification in a primary clarifier may produce such high reductions in suspended solids and BOD that secondary treatment is not needed to meet effluent requirements.

PRIMARY CLARIFIER APPLICATION

Effective dispersion of the treating chemical into the sewage is a prime requirement for chemical utilization. Existing sewage primary clarifiers are liquid-solids separators, not chemical reactors. A mixing unit should be installed just ahead of the clarifier, or the internal mechanism of the clarifier should be modified to include adequate mixing of chemical and sewage. The practice of adding the chemical into a manhole upstream of the clarifier, or into the wet well if the sewage is pumped may be satisfactory in some cases.

If lime is the treating chemical the mixing requirements are more complicated than for aluminum or iron salts. The clarifier is modified to provide for sludge recirculation to stabilize supersaturated calcium carbonate to prevent severe scaling. Provision must be made for reducing the high pH of the clarifier effluent before disposal into a stream, or into a secondary aerobic biological system, or for treatment in activated carbon reactors. This is usually done by recarbonation or mineral acid addition in a flash mixer.

SECONDARY BIOLOGICAL REACTOR APPLICATION

Lime is not added directly in biological systems because the high pH would kill or seriously damage the bacteria. The two principal aerobic reactors, activated sludge and trickling filter pose different problems.

For activated sludge the metal salts can be added toward the end of the aeration basin taking advantage of the turbulence created by the aeration system to give effective mixing. At this point all of the organic and condensed phosphorus has been hydrolyzed by enzymes to orthophosphate. The return of a substantial volume of sludge to the inlet end of the aeration basin utilizes any excess metallic hydroxide. It is difficult to evaluate this in conventional treatment, but at Milwaukee, Wisconsin this effect is clearly shown. Here there are two parallel systems. The East 115 mgd (435,320 m^3/day) unit is treated with 15 mg/l Fe from pickle liquor added to the screened sewage at the inlet to the aeration basin. During a test period the excess sludge from the East plant was added to the screened sewage at the inlet of the West plant 85 mgd (321,760 m^3/day), but no pickle liquor was added. The influent

P of 10.1 mg/l was reduced to 0.6 mg/l in the effluent from the West plant with the only source of chemical being the excess in the excess sludge from the East plant (21). With wastewaters having a high phosphate load but low BOD, the amount of cell synthesis may be so small that the sludge wastage required to dispose of the chemical floc may deplete the biomass so the aerobic system eventually fails. In some areas the alkalinity of the source water may be so low that it is inadequate to neutralize the acid radical of the applied chemical. An alkali must be added to maintain the pH in a range satisfactory for biological activity.

With modern recirculating trickling filters the metallic salts should be added to the inlet of either the primary or secondary clarifier. Performance at Fairborn, Ohio (22) was not satisfactory when the chemical was added at the filter inlet. Of the several types of recirculation (a) filter outlet to filter inlet, (b) filter outlet to primary clarifier inlet, (c) final clarifier outlet to filter inlet, and (d) final clarifier outlet to primary clarifier inlet, only in (b) and (d) should the chemical be added to the suction side of the recirculation pump. One plant scale study (22) showed more effective use of the chemical when the feed was split between the primary and final clarifiers.

SECONDARY PHYSICAL-CHEMICAL REACTOR APPLICATION

The best developed of the physical-chemical processes involves a primary precipitation-clarification unit for removal of phosphates and suspended matter followed by activated carbon columns for removal of soluble organic matter. There is some biological activity in the first unit of the carbon column series, but it does not produce an appreciable amount of additional phosphorus removal (23). This biological activity will cause conversion of some of the organic and condensed phosphorus to the ortho form, making possible additional P removal by chemical addition in a final clarifier.

TERTIARY BIOLOGICAL REACTOR APPLICATION

A properly operated biological system will cause complete conversion of organic and condensed phosphates to orthophosphate. In a tertiary chemical precipitation-clarification unit, the feed to which will be essentially free from biological floc, chemical treatment will produce a very low P residual. This may be as low as 0.1 mg/l P, particularly if the reactor is followed by a filter to remove any phosphorus-laden precipitate from the reactor overflow. The usual precautions of good mixing and pH control should be observed.

PHYSICAL PROCESSES

Plain sedimentation in a clarifier removes very little phosphorus. This is also true of mechanical filtration. The rapidly developing membrane processes do give very good phosphorus removal (24). The effluent, or the product water to use membrane terminology, is of very high quality. The cost is high, and probably will remain so, so it will be used only in those cases where a very high quality effluent is needed. It should be remembered that the membrane processes do not destroy any of the pollutants. They are concentrated into a small volume, perhaps only 5% to 10% of the original volume. They can now be treated in smaller structures, but the chemical and power costs will not be reduced. Membrane technology is not ready for general use.

SECTION VI

DISPOSAL OF SLUDGE FROM PHOSPHORUS REMOVAL PROCESSES

Ultimate disposal of sludge from phosphorus removal operations has received some attention. It may prove to be one of the most difficult of the unit processes to evaluate because of the environmental pollution problems of any of the workable sludge disposal methods.

The classical method of anaerobic digestion of the volatile organic content of the sludge with land disposal of the inert organic humus after dewatering and return of the supernatant to the head of the treatment plant poses the following problems.

1. With luxury uptake and lime precipitation the insolubilized phosphorus compounds are redissolved and are not removed from the system (27).

2. With precipitation of the phosphorus by aluminum or iron salts the insolubilized phosphorus is not redissolved (28)(29)(30) but does make a large increase in the final residue. The two or threefold increase in the mass of sludge before digestion (31)(32)(33) with chemical precipitation will make an even larger percentage increase of digested sludge mass.

Disposal of undigested sludge on land after additional chemical treatment to stabilize the sludge may have fewer problems than any of the other methods. Soil has a very high capacity to fix phosphates, so very little, if any, should reenter the aqueous environment (34). The iron and aluminum residues will have no adverse effects (35). An unknown factor that may be objectionable is the potential for resolution of some of the heavy metals that have been concentrated in the sludge.

Incineration will destroy the organic content of sludges, and effectively dewater the mineral residue.

1. Calcining lime treatment sludges for recovery for reuse of the calcium oxide content makes a very large reduction in the inert mass, largely calcium phosphate and magnesium oxide, for ultimate disposal. The practice at South Tahoe (18) is treated in great detail, and this publication should be studied by anyone planning lime treatment.

2. Incineration of sludge from luxury uptake does not make a significant increase in mass over that from ordinary activated sludge operation.

3. Incineration of sludge from aluminum and iron salt precipitation leaves practically all of the metal either as the dehydrated metal phosphate or the oxide. Some work has been done by a committee of the American Water Works Association on recovery of aluminum hydroxide precipitate by treatment with sulfuric acid. It is possible processes for recovery of the metal by acid treatment of the combined phosphate and oxide residues may be developed. For the present, land fill appears the best method of disposal of the residue. The amount can be calculated from the amount of treating chemical used, assuming the metal not used to precipitate the phosphate will be present as the oxide.

4. Any incineration process must comply with local air pollution control regulations.

SECTION VII

FULL-SCALE PLANTS

The Environmental Protection Agency and its predecessors have funded more than fifty research and development programs to test the practicality of numerous proposed phosphorus removal methods. Commercial organizations have made many full-scale field tests to demonstrate their equipment and chemicals. Municipalities have also carried out studies in their own plants. Out of all this work has come the evidence that chemical precipitation with lime, aluminum, and iron salts is the only assured practical method of removing phosphorus from wastewater. Most of the needed design criteria has also been developed during the course of these studies.

There are three areas in the United States where particular emphasis is placed on removal of phosphates from wastewater. These are the Great Lakes, Tampa Bay, Florida, and the Upper Potomac River Estuary. Planning here is typical of other areas.

The following list of phosphorus removal projects from one Chicago consulting engineering firm as of September, 1971 is deemed to be typical.

I. North Shore Sanitary District (Lake County, Illinois).

A. Small Lake Side Primary Plants.

Five plants ranging from 0.6 to 2.6 mgd (2,271 to 9,842 m^3/day).

(a) Method.

Using alum at about 2:1 molar ratio.

(b) Degree of Removal.

8 mg/l P is expected to be reduced to 1-2 mg/l P.

(c) Stage.

Designed, must be in operation by January 1, 1972.

(d) Cost Estimate.

Annual costs vary from about 4.5¢/M gal for the two 2-2.6 mgd (9,842 m^3/day) plants to about 6¢/M gal for the three 0.6-0.7 mgd (2,271-2,650 m^3/day) plants. Capital costs are assumed to be $50,000.00 for each of the five plants.

B. Clavey Road, Highland Park.

Design: 18 mgd (68,137 m^3/day) activated sludge.

(a) Method.

Waste pickle liquor in aeration basin.

(b) Degree of Removal.

8 mg/l P is expected to be reduced to 1 mg/l P.

(c) Stage.

Not yet required.

(d) Cost Estimate.

Annual costs should be about 1.2¢/M gal. Capital costs are expected to be about 1.7¢/design gallon.

C. Waukegan.

Existing 15 mgd plant (56,781 m^3/day) with activated sludge treatment for about 8 mgd (30,283 m^3/day).

(a) Method.

$FeCl_3$ and an anionic polymer added just before primary tanks. Using about 60 mg/l $FeCl_3$ and 0.2-0.5 mg/l polymer.

(b) Degree of Removal.

8 mg/l P is reduced to less than 1 mg/l P.

(c) Stage.

Have been adding FeCl since early September 1971. Polymer dosing equipment to be installed soon.

(d) Cost Estimate.

Probably less than 3¢/M gal at current P levels. Also appear to save substantially on Cl_2 due to improved (suspended) BOD removal. No major capital improvements are needed since $FeCl_3$ dosing and storage facilities exist.

(e) Future.

25 mgd plant (94,635 m^3/day). Will use pickle liquor added in aeration tank when new aeration basins are complete. Annual costs should be 1.2¢/M gal. Capital costs are expected to be about 1.7¢/design gallon.

D. Gurnee.

Currently under design. No plant now. Expected to be similar to Waukegan and Clavey Road.

II. Tampa, Florida.

Existing 36 mgd (136,270 m^3/day) primary; future activated sludge at 54 mgd (204,410 m^3/day).

A. Method.

Alum or $FeCl_3$ to aeration tanks, final filtration.

B. Degree of Removal.

12 mg/l P is expected to be reduced to less than 1.2 mg/l P.

C. Stage.

Early design.

D. Cost Estimate.

About 7-8¢/M gal annual costs. This includes all solids handling. Capital cost of about 2.6¢/design gallon, including solids handling. Filtration costs are not included. The major portion of the capital cost was due to assigning some of the incinerator costs to this estimate.

III. Alexandria, Virginia.

Existing 18 mgd (68,137 m^3/day) trickling filter. Future 54 mgd (204,410 m^3/day) roughing bio-filter physical-chemical plant.

A. Method.

Alum precipitation in clarifiers following upflow carbon columns; followed by rapid sand type filtration. Probably will use long chain anionic polymer with alum.

B. Degree of Removal.

12.5 mg/l total P (10 mg/l P soluble) is expected to be reduced to less than 0.2 mg/l P at design annual average flow.

C. Stage.

Final design being completed.

D. Cost Estimate.

None available.

IV. Ashland, Wisconsin.

1.6 mgd activated sludge (6,057 m^3/day).

A. Method.

Alum added to the aeration tanks.

B. Degree of Removal.

7 mg/l P is to be reduced to less than 1.1 mg/l P.

C. Stage.

Design completed.

D. Cost Estimate.

About 3-4¢/M gal total annual costs and about 1¢/design gallon capital costs. Incremental solids handling costs were assumed negligible in this application.

PARTIAL LIST OF FULL-SCALE PLANTS, OPERATIONAL OR PLANNED

Location	Capacity		Treatment		Effluent P
	mgd	m^3/day	Stage	Type	mg/l
Amarillo, Texas Southwestern Public Service Company	13	49,210	Tertiary	Lime	0.3
Baltimore, Maryland	20	75,708	Act.Sludge	Luxury	0.7
Blue Plains Plant Washington, D.C.	309	1,169,684	Act.Sludge	Alum	3.0
			Tertiary after Denitrification and Filter		0.1
Bay City, Michigan	12	45,725	Primary	$FeCl_2$-Polymer	2.0
Chicago South Creek Chicago, Illinois	30	113,562	Secondary	Alum	1.0
Colorado Springs, Colorado	2	7,570	Tertiary	Lime	0.5
Detroit, Michigan	750	2,839,100	Act.Sludge	Pickle Liquor	1.0
El Lago, Texas	0.5	1,890	Primary	Alum	2.0
Ely, Minnesota	1.5	5,678	Tertiary	Lime-Filter	0.05
Grand Rapids, Michigan	45	170,340	Act.Sludge	$FeCl_3$-Polymer	1.0
Hatfield Township, Pennsylvania	5	18,900	Primary	Lime	2.0

PARTIAL LIST OF FULL-SCALE PLANTS, OPERATIONAL OR PLANNED - Cont'd

Location	Capacity		Treatment		Effluent P
	mgd	m^3/day	Stage	Type	mg/l
Holland, Michigan	4	15,120	Primary	Lime	2.0
Nevada Power Co. Las Vegas, Nevada	6	22,712	Tertiary	Lime	0.3
Hyperion Plant Los Angeles, Calif.	100	378,540	Act.Sludge	Luxury	0.5
Manassas, Virginia	1	3,785	Act.Sludge	Alum Sodium Aluminate	1.0
Milwaukee, Wisconsin					
East Plant	115	435,320	Act.Sludge	Pickle Liquor	0.23
West Plant	85	321,760	Act.Sludge	Excess Sludge from East Plant	0.6
El Paso Products Co. Odessa, Texas	5	18,900	Tertiary	Lime-Filter	0.1
Owosso, Michigan	6	22,712	Primary	Lime-Alum	2.0
Painesville, Ohio	5	18,900	Primary	$FeCl_3$-Polymer	2.0
Piscataway, Maryland	5	18,900	Secondary	Lime	1.0
Pomona, California	2	7,570	Act.Sludge	Alum Sodium Aluminate	0.5

PARTIAL LIST OF FULL-SCALE PLANTS, OPERATIONAL OR PLANNED - Cont'd

Location	Capacity		Treatment		Effluent P
	mgd	m^3/day	Stage	Type	mg/l
Richardson, Texas	1.6	6,060	Trickling Filter	Alum 20% Primary 80% Final	0.5
Rochester, New York	100	378,540	Primary	Lime	2.0
Rocky River, Ohio	10	37,854	Primary	Alum-Polymer	2.0
San Antonio, Texas	30	113,560	Act.Sludge	Luxury	0.5
Seattle, Washington	24	90,850	Act.Sludge	Alum	0.5
South Lake Tahoe, Nevada	7.5	28,391	Tertiary	Lime	0.16
Trenton, Michigan	6	22,710	Act.Sludge	Pickle Liquor	0.6
Waukegan, Wisconsin	15	56,780	Act.Sludge	$FeCl_3$-Polymer	1.0
Xenia, Ohio	1	3,785	Secondary	Alum Sodium Aluminate	1.0

This partial list of full-scale phosphorus removal plants, covering a capacity range from 750 mgd (2,839,100 m^3/day) to 0.5 mgd (1,890 m^3/day), shows the wide variety of chemicals to be used and the several different points of application of the chemicals. No tabulation tells even a reasonably complete story. There are several factors that should be considered in evaluating the data, particularly the effluent P concentration.

Although 10 mg/l P is generally accepted as the average concentration, actual variation throughout a 24-hour period may range from 2.0 mg/l P to 25 mg/l P (20). With the variation in rate of flow and phosphorus concentration that must be expected, it is difficult to pace chemical feed to chemical demand to approximate optimum results. Automatic control equipment to measure both rate of flow and concentration of phosphorus and integrate these into a signal that will proportion chemical feed to chemical demand is expensive, but can be used if consistently low P residuals are required.

The solubility of the P precipitates will vary with changing conditions, of which pH is the most important. As an example, the solubility of $AlPO_4$ varies with pH (36):

pH	Solubility mg/l P
5.0	0.03
6.0	0.01
7.0	0.30

An excess of the reacting chemical is also an important factor in more effective removal of P. Analysis of data from a large number of plant scale studies under a wide variety of conditions establishes a reasonably uniform chemical demand for various per cent reductions from a 10 mg/l P concentration as follows (37):

P Reduction	Al:P		Residual P
	Mole Ratio	Weight Ratio	mg/l
75%	1.38:1	1.2:1	2.5
85%	1.72:1	1.5:1	1.5
95%	2.30:1	2.0:1	0.5

Once the basic equipment for storage and feeding of chemicals is installed it costs little more to provide for multiple points of application. In a biological system chemical precipitation in the primary clarifier will remove most of the phosphates and improve the removal of organic suspended solids over plain sedimentation to reduce the BOD load on the aerobic reactor. The residual phosphates, largely in the organic and condensed forms

will be hydrolyzed to the ortho form by enzymatic action in the biological unit. A second application either toward the end of the aerobic reactor or in the flow channel to the final clarifier can produce very low residual P. Note the two examples in the list of plants. Richardson, Texas applies 20% of the alum in the primary and 80% in the final clarifier to get a residual P of 0.5 mg/l without final mechanical filtration. The Blue Plains plant at Washington, D.C. splits the feed of alum between the activated sludge reactor, using enough chemical to reduce P to 3.0 mg/l, and after biological denitrification uses additional alum to the final clarifier followed by mechanical filtration to reduce the P to 0.1 mg/l.

If iron salts are to be the precipitating agents, there are several important factors to consider. Pickle liquor, in which the iron is in the ferrous form, is one of the cheapest chemicals to use for P removal. For a given weight of iron used, phosphate removal efficiency is higher for ferrous iron than for ferric iron from a stock source when the ferrous iron is completely oxidized in situ resulting in homogenous generation of ferric iron (19). Excess pickle liquor added to the primary clarifier with subsequent aeration in an aerobic reactor, or the addition of pickle liquor to the activated sludge aeration basin early enough to assure complete conversion of ferrous to ferric iron is one of the most economical precipitation techniques. However, addition of iron salts in the final clarifier, particularly ferrous salts where there is little oxidation to the ferric form, may result in objectionable iron leakage in the effluent (38).

If ferric salts are to be used, provision to dilute the concentrated stock solution to the dilute solution for application to the wastewater should provide for a minimum time lag between dilution and feeding. The dilute ferric salts hydrolyze on aging, with loss of phosphate precipitation effectiveness (9).

Alexandria, Virginia is a good example of getting the best of both biological and physical-chemical systems. Utilizing the existing 18 mgd (67,137 m^3/day) trickling filters as part of an expanded 54 mgd (204,410 m^3/day) roughing biofilter physical-chemical plant including activated carbon adsorption followed by alum precipitation in a clarifier with rapid sand filters reduces the phosphorus in the final effluent to 0.2 mg/l. The enzymatic conversion of organic and condensed phosphorus compounds to the ortho form in the biofilter makes this possible.

The lowest residual phosphorus in this tabulation is the 0.05 mg/l P for Ely, Minnesota. The effluent from this plant flows into Lake Shagawa which has had serious eutrophication problems.

The existing trickling filter plant is followed by a new lime precipitation plant with final mechanical filters. The contractor has guaranteed that the phosphorus level in the final effluent will not exceed 0.05 mg/l P. Chemical control by pH measurement will assure variation in chemical feed to match chemical demand.

Details of the source and characteristics of the various treating chemicals are thoroughly covered in the EPA Phosphorus Removal Manual (17). There are many problems in storage and handling of the chemicals that are also covered in this manual.

Chemical Dosages and Unit Costs

	Lime mg/l	Alum mg/l	Ferric Chloride mg/l	Polymer mg/l
Dosage For Initial P of 10 mg/l				
80% removal	175	125	55	0.5
90% removal	350	175	75	0.5

	Lime $/ton	Alum $/ton	Ferric Chloride $/ton	Polymer $/lb
Unit Cost of Chemicals				
1 mgd	28	50	120	1.70
10 mgd	26	48	115	1.60
100 mgd	25	46	110	1.50

SECTION VIII

COSTS

The cost for building and structures can vary widely for the same capacity. Land values, architectural design, completeness of office and laboratory equipment, and the need to house equipment in cold countries that can be left open in warm climates are all important cost variables. For process equipment the cost need not vary so much except for the degree of automation. Operating costs for chemicals will be reasonably consistent because of the general availability of the treating chemicals. Labor costs will vary widely, both as to pay rates and the number of personnel. The data given by Koenig (39) for municipal water filter plants will apply to municipal waste water plants. All of the cost data is based on chemical treatment. A few comments on the only potential non-chemical process are in order.

Costs for metabolic luxury uptake of phosphorus are negligible. As long as aerobic conditions are maintained in the aeration basin and final clarifier, and the excess sludge does not reenter the system there are no added costs for P removal. Some of these systems are operated at very high dissolved oxygen concentrations compared to the DO required for BOD control, and this is an added cost. The experience at the Hyperion plant at Los Angeles, California where effective luxury uptake is obtained with no more than 2.0 mg/l DO at any point in the system suggests that the high DO concentrations may not be necessary. For the very low values (0.1 mg/l P) of which the process is capable it is necessary to remove by filtration the carry-over of high P containing suspended solids from the final clarifier. If the process ever becomes controllable and can be utilized generally, it may supplant chemical addition processes in activated sludge plants.

It is not practical to analyze costs for the many combinations of treatment systems, both for new plants and improvement of existing plants, but the attached table gives data that can be extrapolated to give a reasonable estimate of most arrangements. The most detailed and usable cost information is in the EPA Technology Transfer Process Design Manual for Phosphorus Removal (17). Smith and Michael (25) and Kumar and Clesceri (26) have excellent cost analyses.

The data in this tabulation is necessarily an average of many specific reports and a compromise that averages out to give figures that are usable. In the chemical costs it is assumed that polymers for improved coagulation will be used. Of the many means of sludge disposal, hauling to land disposal is selected for this estimate.

TREATMENT PLANT COSTS FOR PHOSPHORUS REMOVAL

CAPITAL INVESTMENT

	Cost in Dollars for Plant Size		
	1 mgd 3,785 m^3/day	10 mgd 37,854 m^3/day	100 mgd 378,540 m^3/day
Building and Structures	15,000	40,000	90,000
Process Equipment Installed			
Lime	45,000	150,000	410,000
Aluminum Salts	35,000	96,000	300,000
Iron Salts	35,000	85,000	250,000

OPERATING AND MAINTENANCE COSTS

	Dollars per Day for Plant Size		
	1 mgd 3,785 m^3/day	10 mgd 37,854 m^3/day	100 mgd 378,540 m^3/day
Labor			
Operating	35	100	200
Maintenance	18	90	225
Amortization			
Lime	13.20	41.80	109.15
Aluminum Salts	10.90	29.80	86.50
Iron Salts	10.95	29.48	74.80
Chemicals and Sludge Disposal Costs			
80% P Removal			
Lime	36.50	329.45	3293.20
Aluminum Salts	40.45	382.65	3643.20
Iron Salts	43.05	389.15	3888.75
90% P Removal			
Lime	66.35	584.75	5303.20
Aluminum Salts	53.70	509.30	4933.20
Iron Salts	56.10	508.75	4998.20

TREATMENT PLANT COSTS FOR PHOSPHORUS REMOVAL - Cont'd

OPERATING AND MAINTENANCE COSTS - Cont'd

	Dollars per Day for Plant Size		
	1 mgd 3,785 m^3/day	10 mgd 37,854 m^3/day	100 mgd 378,540 m^3/day
Total Daily Operating and Maintenance Costs			
80% P Removal			
Lime	102.70	561.25	3827.35
Aluminum Salts	104.35	602.45	4154.70
Iron Salts	100.45	608.63	4388.55
90% P Removal			
Lime	132.55	816.55	5837.35
Aluminum Salts	117.60	729.10	5444.70
Iron Salts	120.05	728.23	5498.00

SECTION IX

ACKNOWLEDGEMENTS

The cooperation of the officials and operators at the many plants that were visited is acknowledged with appreciation. Particular gratitude is due to Dr. C. H. Connell, Texas City; William F. Garber at the Hyperion Plant in Los Angeles; and to William N. Wells at San Antonio, Texas.

Dr. Thomas E. Wilson, Greeley and Hansen, Chicago, Illinois was particularly helpful by permitting use of data on the many phosphorus removal plants under design in the Company's office.

The Contract Project Officer, Dr. Robert L. Bunch furnished a large amount of information not yet in print. I wish to express my sincere appreciation for his help and guidance.

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SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

1. Report No. | 2. | 3. Accession No. W

4. Title: Evaluation of Processes Available for Removal of Phosphorus from Wastewater

5. Report Date

6.

7. Author(s): Cecil, Lawrence K.

8. Performing Organization Report No.

10. Project No.

9. Organization:
Lawrence K. Cecil, P.E.
Consulting Chemical Engineer
Tucson, Arizona 85704

11. Contract/Grant No.: Contract 14-12-581

13. Type of Report and Period Covered

12. Sponsoring Organization

15. Supplementary Notes

16. Abstract

The more important treatment processes for removal of phosphorus compounds from municipal wastewater are evaluated for practicality, cost, and impact on the quality of the treated effluent. The bewildering number of options for the designer in the selection of treating processes, chemicals to be used, and the point or points of chemical application are discussed. A detailed list of phosphorus removal projects in the office of one consulting engineer is given as an example of phosphorus removal projects under design. A list of full-scale phosphorus removal plants, already in operation or planned, shows the type of treatment selected and the operating results expected. Various methods of ultimate sludge disposal are discussed.

17a. Descriptors: Sewage Treatment, Phosphates, Biological Treatment, Chemical Precipitation, Activated Sludge, Physical Processes, Tertiary Treatment, Process Selection.

17b. Identifiers: Sludge Production, Lime, Alum, Iron, Aluminate, Cost.

17c. COWRR Field & Group: 05D

18. Availability

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages

22. Price

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